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SHIELDING REQUIREMENTS FOR THE NASA PLUM BROOK HB-6 BEAMHOLE RADIATION EFFECTS FACILITY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

The calculational methods and results used to design a shield assembly for the NASA Plum Brook Reactor HB-6 beamhole facility are described herein. The function of this shield assembly is to provide adequate biological protection during reactor operation and to permit personnel access to a test chamber after shutdown.

Radiation sources examined during reactor operation were neutrons and gamma rays scattered by an experimental package in the test chamber, direct core radiations, and radiation through rectangular slits which may be formed by misalinement of shield sections. Fission product decay gammas and neutron-induced gamma activity in the test chamber were the important radiation sources investigated after shutdown.

The bulk of the calculations was performed by specialized digital computer shielding programs which accounted for considerable detail of the core-beamhole geometry. Calculational results compare favorably with experimental measurements on the final shield assembly.

INTRODUCTION

A program was initiated to investigate the effects of neutron and gamma radiation on the properties of electrical components (ref. 1). The source of fast neutron and gamma radiation selected was the HB-6 beamhole of the Plum Brook Reactor (PBR) facility (fig. 1).

A complete description of the facility is given in reference 1. The closed end of this beamhole abuts the beryllium reflector of the PBR core; the open end is accessible at the north face of quadrant B, where the nominal 15-inch-diameter (38. 1 cm) fast neutron beam emerges. Calculated unshielded dose rates of about 1×10^{4} rem per hour from fast neutrons and 1×10^{5} rem per hour from gamma rays emanating from the beamhole into quadrant B indicated the need for biological shielding of these direct radiations. In addition, insertion of an experiment package in the beam gives rise to a scattered dose component at angles to the direct beam and thus creates the need for additional personnel radiation protection. This report presents a summary of the calculational methods and results used to design a biological shield assembly for the HB-6 test facility. The function of this shield assembly is to provide adequate biological protection during reactor operation and to permit personnel access to a test chamber in the shield assembly after shutdown. The approach used in designing the shield is presented in the following paragraphs.

The average allowable radiation exposure rate in quadrant B was set at 2.5 millirem per hour both during reactor operation and after shutdown. This rate was based on a maximum whole-body exposure of 20 millirem for an eight-hour day with a maximum allowable exposure rate of 20 millirem per hour. Radiation sources examined during reactor operation were direct and scattered radiations. Direct core radiation sources treated were prompt-fission neutrons and prompt-fission gammas. Direct out-of-core radiation sources considered were restricted to gamma rays resulting from the capture of neutrons in the PBR core structure (aluminum and water). Scattered radiation sources examined were neutrons and gamma rays scattered by an experiment package located on the beamhole centerline inside the test chamber. Radiation sources investigated after shutdown were core fission product decay gammas and neutron-induced gamma activity in the test chamber.

The calculation of required shield thicknesses relied heavily on the use of shielding computer codes. Specifically, a line-of-sight shield code was used to compute direct neutron and gamma source attenuation during operation and gamma attenuation after shutdown, while scattered-gamma-ray shield requirements were calculated with a single-scatter shielding code. Also, dose rates from neutron-induced gamma activity were computed with a neutron activation code.

The required attenuation was obtained in terms of iron and borated paraffin thicknesses because of their good attenuation characteristics, low cost, and ease of fabrication. In addition, consideration was given to the presence of another shielding assembly in quadrant B which had to mate with the HB-6 shield assembly with a minimum of alteration of materials and dimensions.

The final step in the shield design procedure was an operational shield test to determine if radiation levels on the shield surface exceeded the design specifications and to give data for correcting any unsatisfactory conditions.

The final shield assembly consisted of a stacked array of interlocking blocks designed to reduce radiation streaming between block interfaces. The shield blocks were formed by filling mild steel and aluminum shells with a borated paraffin mixture, with conduit and water pipes built in where required.

At the request of the radiation effects experimenter many miscellaneous calculations were performed, but only those of general interest are reported herein. These calculations include determination of a fast-neutron flux map to evaluate the spatial variation of the radiation environment in the test chamber and an estimate of the effect of flooding both the HT-1 duct and the HB-6 beamhole on the fast-neutron flux and gamma dose rate in the test chamber. Included in the appendix are brief descriptions of the digital computer codes used in this report.

DESCRIPTION OF CORE-BEAMHOLE GEOMETRY

The HB-6 beamhole is formed from a nominal 15-inch-(38.1 cm) diameter aluminum thimble with a length to diameter ratio of about 10, which opens into the north face of quadrant B, penetrates the core shielding, and terminates 1/2 inch (1.3 cm) from the beryllium blocks of the primary reflector (fig. 1). This thimble is surrounded by a shield liner divided into three axial sections. At the core-reflector end of HB-6, the liner is composed of alternate layers of water and iron which act as thermal shields. The central shield liner is high-density concrete, and the last section is a mixture of steel shot and water. Located within the thimble is a cylindrical, compartmentalized aluminum tank which can be flooded selectively to vary the neutron flux or flooded completely to provide gamma attenuation during shutdown. When empty, the tank presents a total thickness of 2.5 inches (6.4 cm) of aluminum perpendicular to the neutron beam. In addition, a 1/4-inch (0.64 cm) boral plate is provided to reduce thermal neutron flux. Cooling requirements for the boral plate are handled by water lines which present a 1-inch (2.5 cm) water thickness to the beam.

Of special interest is the location of a horizontal test hole HT-1. As shown in figure 2, this 9-inch-(23 cm) diameter duct influences core radiations reaching the HB-6 beamhole. The HT-1 duct is either filled with water or voided depending on the experiment being conducted in it.

Another factor affecting the radiation reaching the HB-6 duct is the shim-control rod position in the core. As shown in figure 3, moving the rods out from 15.4 to 27.8 inches (39.1 to 70.6 cm) can produce a change in power level of a factor of 2 across a projection of the HB-6 duct.

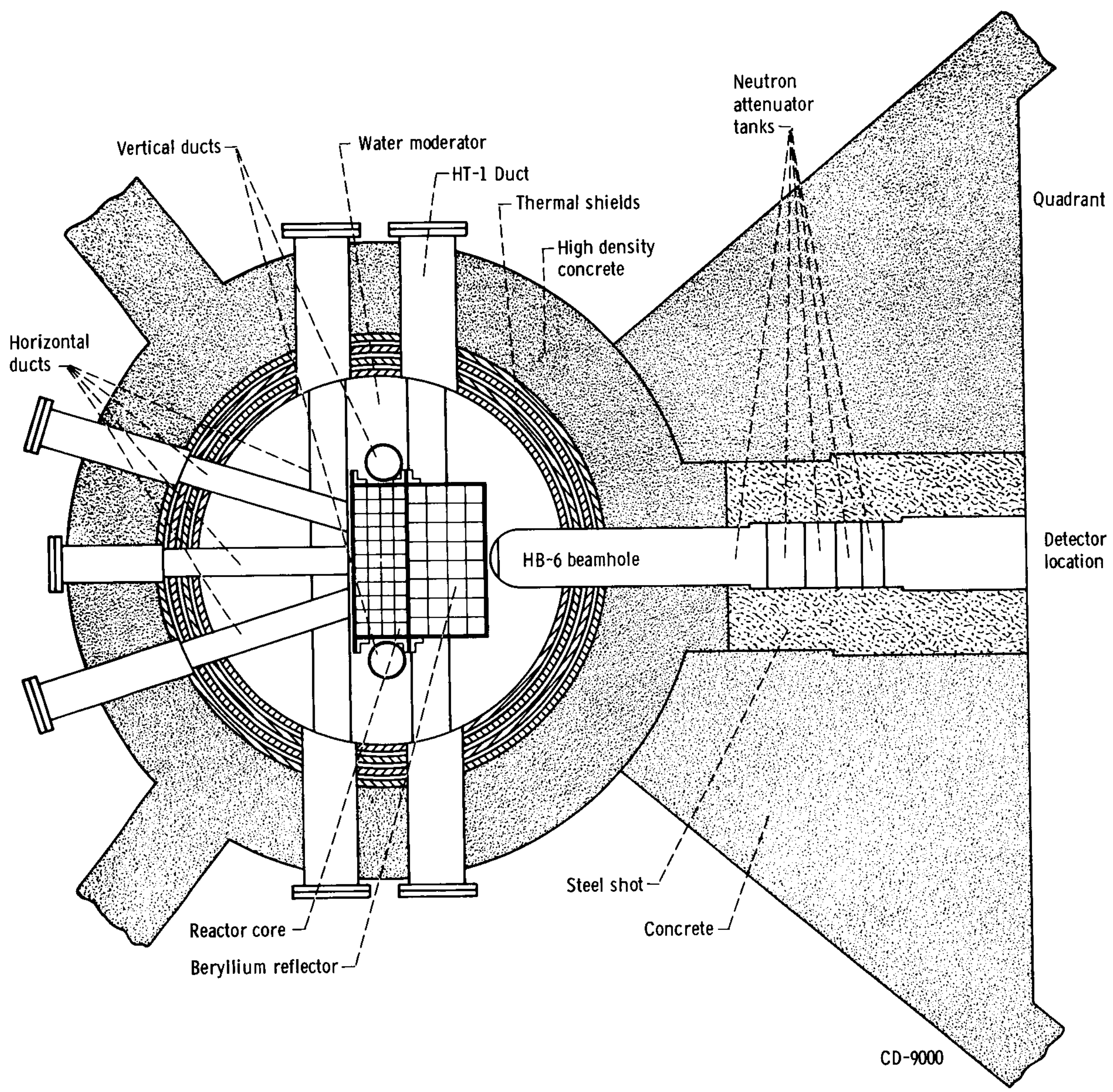


Figure 1. - Plan view of core-beamhole geometry.

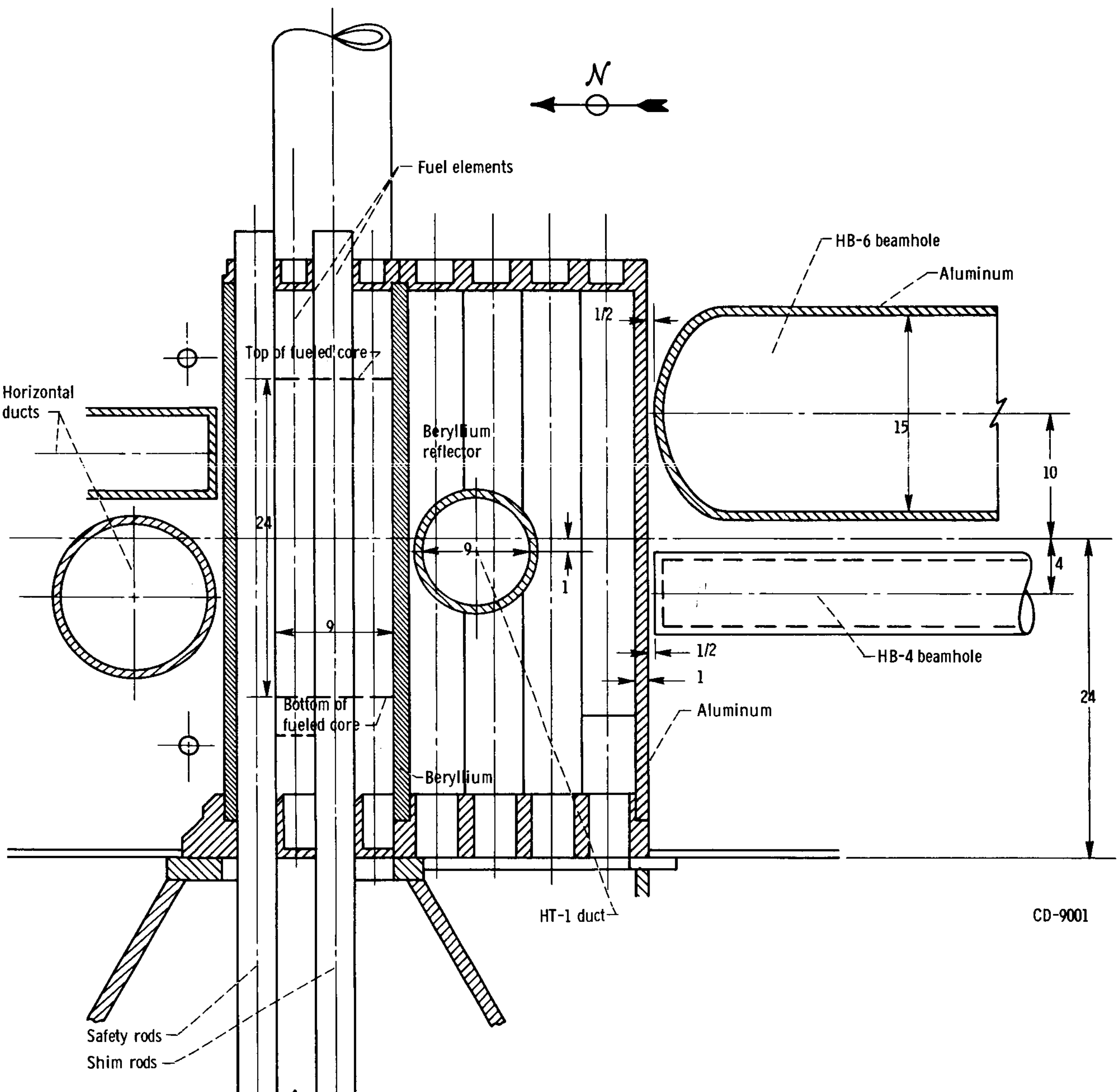


Figure 2. - Detailed core-beamhole geometry. (Side view.) (All dimensions are in inches.)

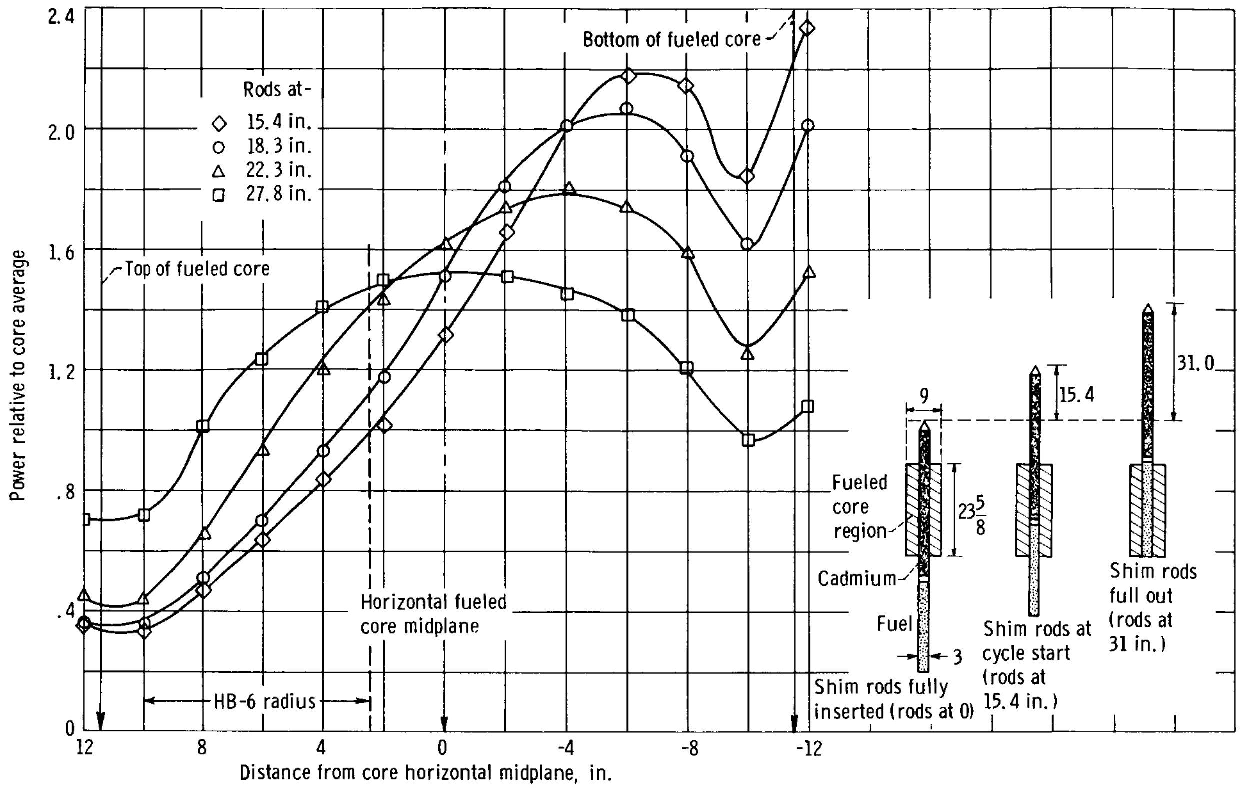


Figure 3. - Vertical power distribution for various rod positions. (All dimensions are in inches.)

SHIELD-DESIGN CALCULATIONS

The calculations of required shield thickness for direct, scattered, after-shutdown, and activation radiation sources are summarized in this section. Except for neutron scattering, all calculations were performed by specialized shielding codes with the IBM 7094 computer. A description of these codes is included in the appendix. In general, shield thicknesses were conservatively calculated at a power level of 60 megawatts thermal with spatial core power distributions corresponding to a rods-out or end-of-core-life situation. Axial and radial power distributions in the core were obtained from the measured values reported in reference 2. Unusual details of individual code input such as gamma-ray buildup factors and special geometry considerations are given as required in the following subsections. All attenuation calculations treat either fast neutrons (energy greater than 0.3 MeV or 0.048 pJ) or gamma rays. No attempt was made to calculate shielding requirements for thermal or epithermal neutrons, because the use of borated paraffin was assumed to attenuate these neutrons to tolerance levels.

Direct-Radiation Shield Requirements

The shield thickness required to attenuate direct-beam radiations to less than 2.5 millirem per hour was calculated with QAD line-of-sight computer code (ref. 3). The method of calculation was an iteration procedure wherein shield dimensions were varied until dose rates outside the shield reached tolerance levels. Important details of the geometry input to the QAD code included representation of the PBR core as a slab, inclusion of the existing shielding, and the presence of horizontal and vertical slits in the shield assembly, which could exist if shield sections were misalined. Other aspects of the QAD code input were the use of iron dose-buildup factors for gamma-ray attenuation and the variation of core power distribution.

The iteration procedure indicated that 4 inches (10.2 cm) of iron plus 8.4 feet (2.56 m) of borated[1] paraffin were required to reduce direct neutron and gamma dose rates to less than 1 millirem per hour each on the rear shield surface when all shield sections were perfectly alined. To protect against radiation streaming due to possible misalinement of shield sections, a 1.5-foot-(45.7 cm) thick borated paraffin slab followed by an iron slab of equal thickness was also required at the rear face of the shield assembly.

Scatter-Radiation Shielding Requirements

The placement of an experiment package in the radiation beam emerging from the HB-6 duct gives rise to a scattered neutron and gamma dose component. Estimates of the scattered neutron dose rate were determined with hand calculation methods while gamma scatter was calculated with the Los Alamos G-33 single-scatter digital computer code. The required thickness of the neutron-scatter shield was calculated by assuming (1) that all the neutrons reaching the test package were scattered and (2) that half of these neutrons were elastically scattered with no energy loss and with a $\cos^2\theta$ angular distribution peaked in the forward direction. The other half of the neutrons were assumed to be inelastically scattered with a 20-percent energy loss and an isotropic angular distribution. These assumptions are generally regarded as conservative and should result in some overestimation of the neutron dose rate.

Because of the assumed $\cos^2\theta$ angular distribution, the dose rate to an observer depends not only on the distance to the radiation source and the type of shield material, but also on the angle between the observer and the scattered neutron origin and the orig-

[1]All borated paraffin has been specified to contain 30-weight-percent boric oxide (B_2O_3).

inal flight path of the neutrons. Neutron-removal theory was used to account for attenuation in the shield and should give good results because of the large thickness of hydrogenous material present. Calculations indicated that a minimum of 3 feet (91.4 cm) of borated paraffin would attenuate neutron dose rates to less than 1 millirem per hour for an observer standing adjacent to the test package.

Scatter gamma penetration through an idealized representation of the HB-6 shielding assembly was calculated with the G-33 gamma scatter code. Pertinent input to the code included location of an equivalent point source (obtained from a QAD calculation) in the HB-6 duct at the outer edge of the reflector, and location of a test-package scatter volume inside the test cavity. Thickness of the test package was varied from 2 to 6 inches (5 to 15 cm) at 1-inch (2.5 cm) intervals to determine the effect of configuration on the scatter gamma dose rate at the top surface of the shield. Computer results showed that, for an assumed test-package thickness of 6 inches (15 cm), a shield thickness of 4 inches (10 cm) of iron plus 3 feet (91.4 cm) of paraffin was required to attenuate gamma scatter dose rates to 1.6 millirem per hour or less for an in-quadrant observer 3 feet (91.4 cm) from the shield surface. Dose rates at the shield surface decreased with increasing test-package thickness presumably from the effect of self-shielding.

Figure 4 shows the results of neutron and gamma scatter calculations as a function of scatter angle and position along the HB-6 centerline projection at the top of the shield assembly. As expected, gamma scatter dose rates for the smallest and largest test-package thicknesses of 2 and 6 inches (5 and 15 cm) reach a maximum at about 40° scattering angle, where the shield thickness is a minimum. For test packages less than 6 inches (15 cm) thick, additional shielding may be required.

A comparison of calculated neutron and gamma scatter dose rates with measured dose rates is presented in the section OPERATIONAL SHIELD TEST.

Shutdown and Access Shielding Requirements

Shutdown and activation dose rates were evaluated with respect to radiation hazards to personnel in the test chamber. After reactor shutdown, both the fast-neutron attenuator tanks and the shutdown tank are flooded to provide 94.5 inches (2.4 m) or water shielding between the reactor and the test package. A 2.75-inch (7 cm) tungsten alloy slab is lowered into the duct opening to provide additional gamma attenuation. Shutdown dose rates at the test-cavity location were determined for times up to 10 hours after shutdown after 1000 hours of reactor operation. (Actual reactor operating times are 240 hours per cycle.) The QAD computer code was used to calculate gamma attenuation when all tanks are flooded and the tungsten alloy shield is in place. In figure 5, the results of the QAD calculation are shown, and shutdown gamma dose rate is plotted against

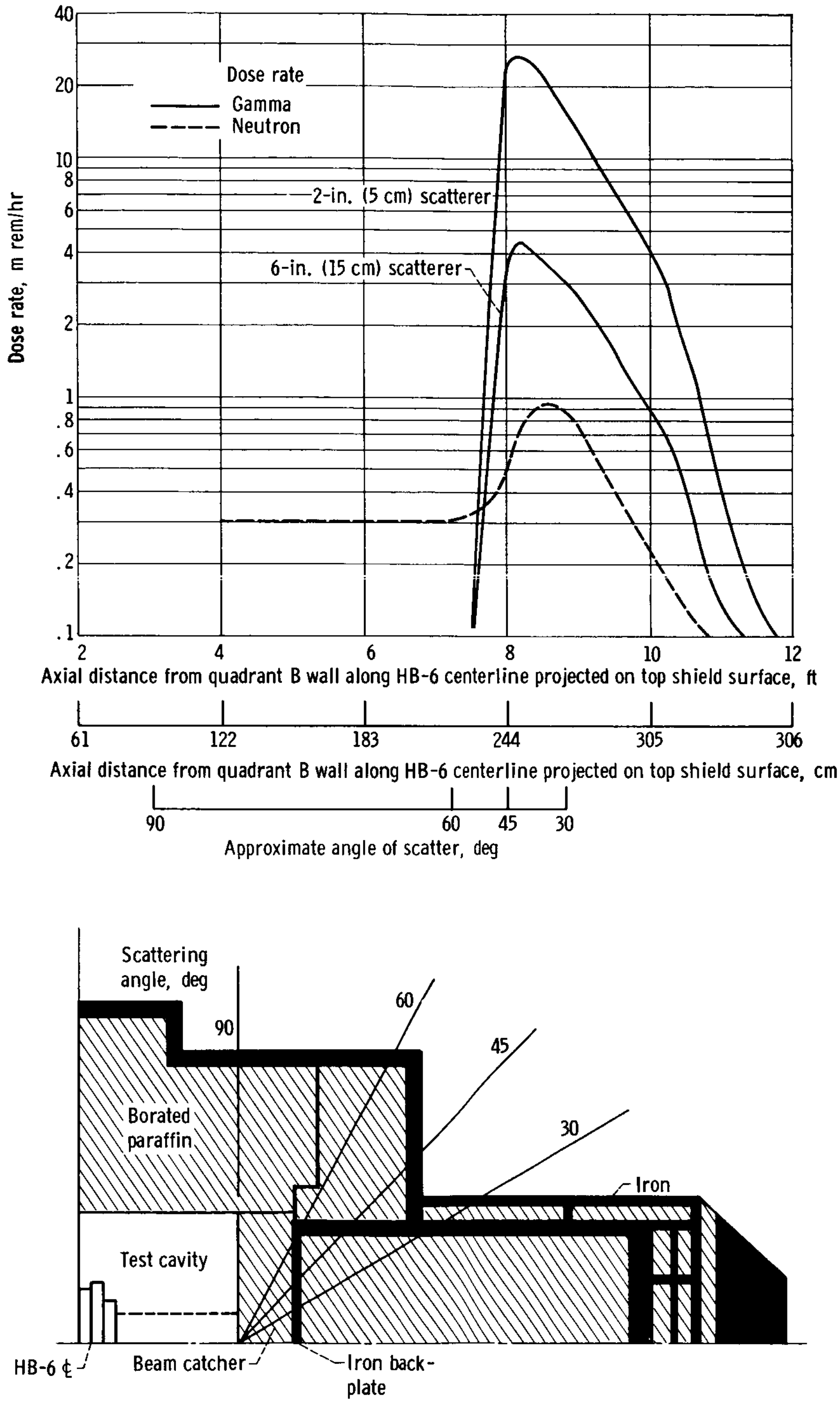


Figure 4. - Scattered neutron and gamma dose rate estimates along shield edge as function of scatter angle.

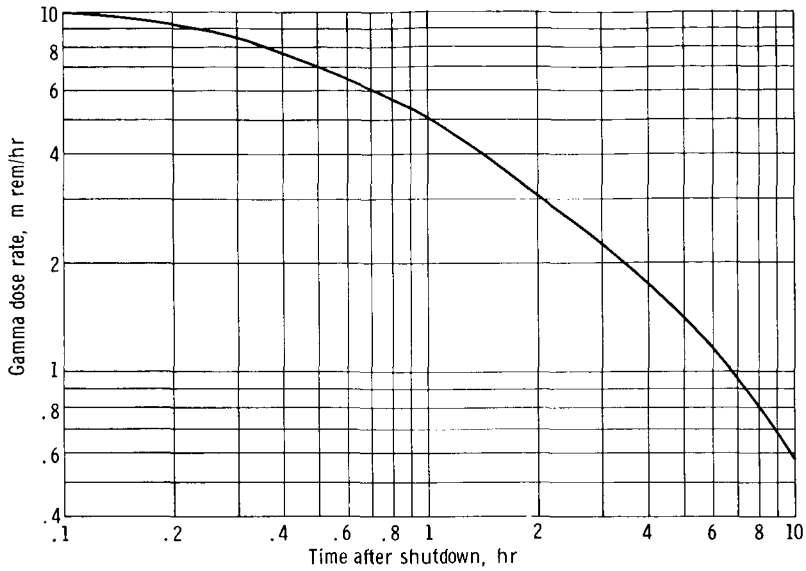


Figure 5. - Shutdown gamma dose rate 1 foot (30.5 cm) from quadrant wall for 1000-hour operation; 94.5 inches (2.4 m) of water in HB-6 duct; 2.75-inch (7 cm) tungsten slab over HB-6 duct.

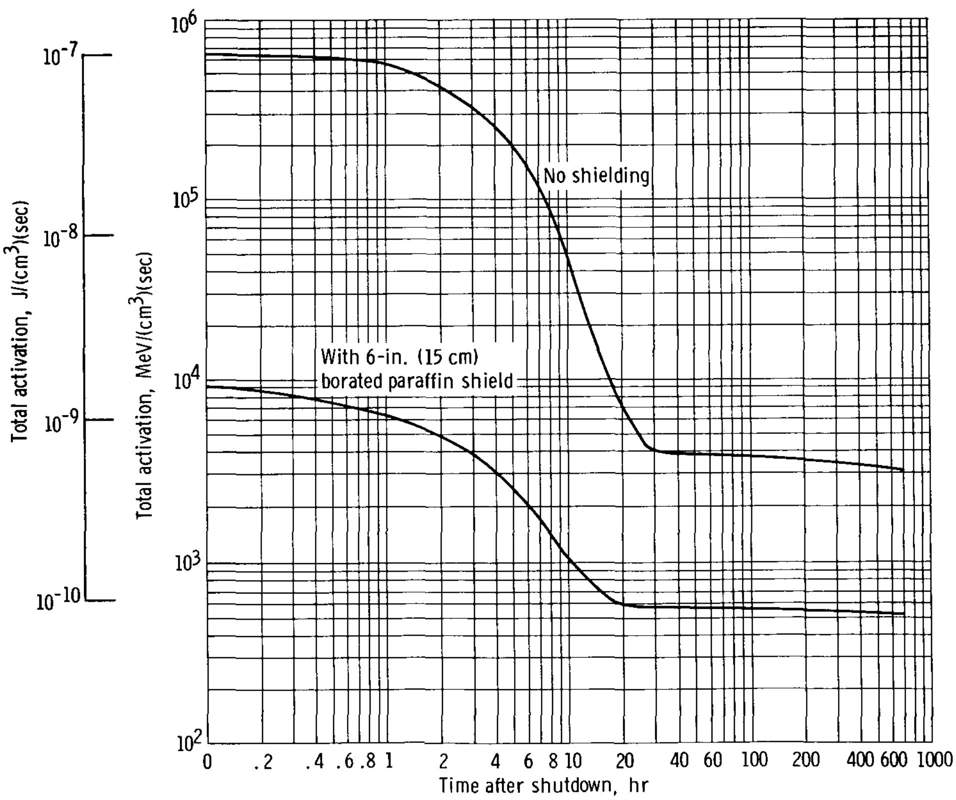


Figure 6. - Activation of iron slab.

time after shutdown. The curve shows a dose rate of 1 millirem per hour at 6.7 hours after shutdown.

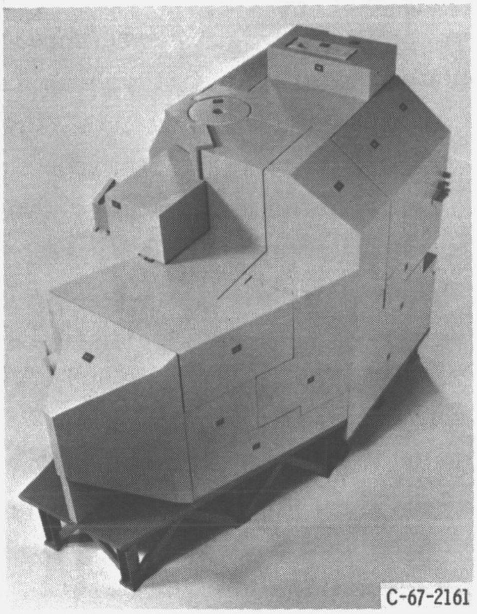
An activation analysis using the NAAC digital computer program (see appendix for code description) was performed to determine induced radio-activity levels in materials exposed to the HB-6 neutron beam. Specifically, it was intended to calculate the activity induced in an existing (part of the HB-4 shield assembly) 1-inch (2.5 cm) iron slab, located directly in the beam beyond the test cavity, as a function of time after shutdown. Two cases were investigated. In the first, no shielding was assumed, and, in the second, a 6-inch (15 cm) borated paraffin shield or "beam catcher" was interposed ahead of the iron plate. For both cases, the reactor was assumed to be operating at 60 megawatts thermal for 240 hours prior to shutdown. Figure 6 illustrates the advantage of the beam catcher in reducing the activation rate after shutdown. Note that an unshielded activation rate of 6.4×10^{5} MeV per cubic centimeter per second ($0.1\ \mu J/(cm^{3})(sec)$) at 0.1 hour after after shutdown corresponds to a dose rate of about 50 millirem per hour in the test cavity. This dose rate is reduced to 0.5 millirem per hour at 1 hour after shutdown for the 6-inch (15 cm) borated paraffin shield. To reduce activation levels further, all interior wall surfaces in the test cavity were lined with aluminum instead of iron.

SHIELD LAYOUT AND DESIGN

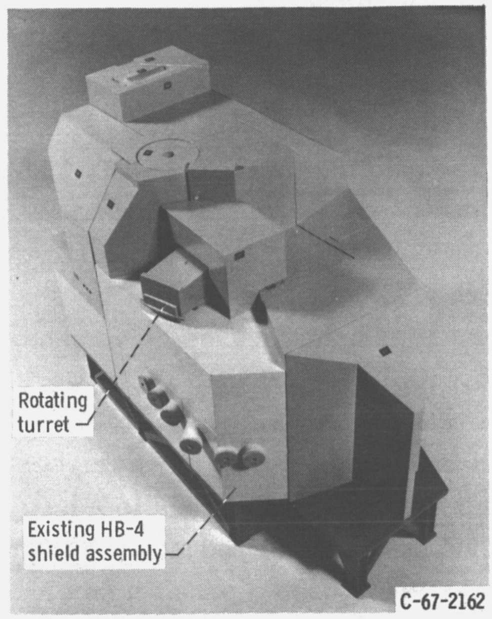
The final shield assembly consisted of stacked blocks formed from borated paraffin-filled steel and aluminum shells. These blocks were designed to interlock to eliminate radiation streaming between the block interfaces.

Figures 7(a) and (b) show a model of the shield assembly as it appears during reactor operation. Note in figure 7(b) the presence of another shield assembly containing additional beamports. This array, which was designed for a prior experiment utilizing the HB-4 beamhole, had to be modified to mate with the HB-6 shield assembly. In addition, much of the existing HB-4 shield assembly served as biological shielding for the HB-6 facility. Figure 7(c) shows plan and elevation views of the shield surface and section views along the HB-6 vertical and horizontal centerlines. Major shield dimensions and materials are shown, and existing HB-4 shielding is denoted by broken lines.

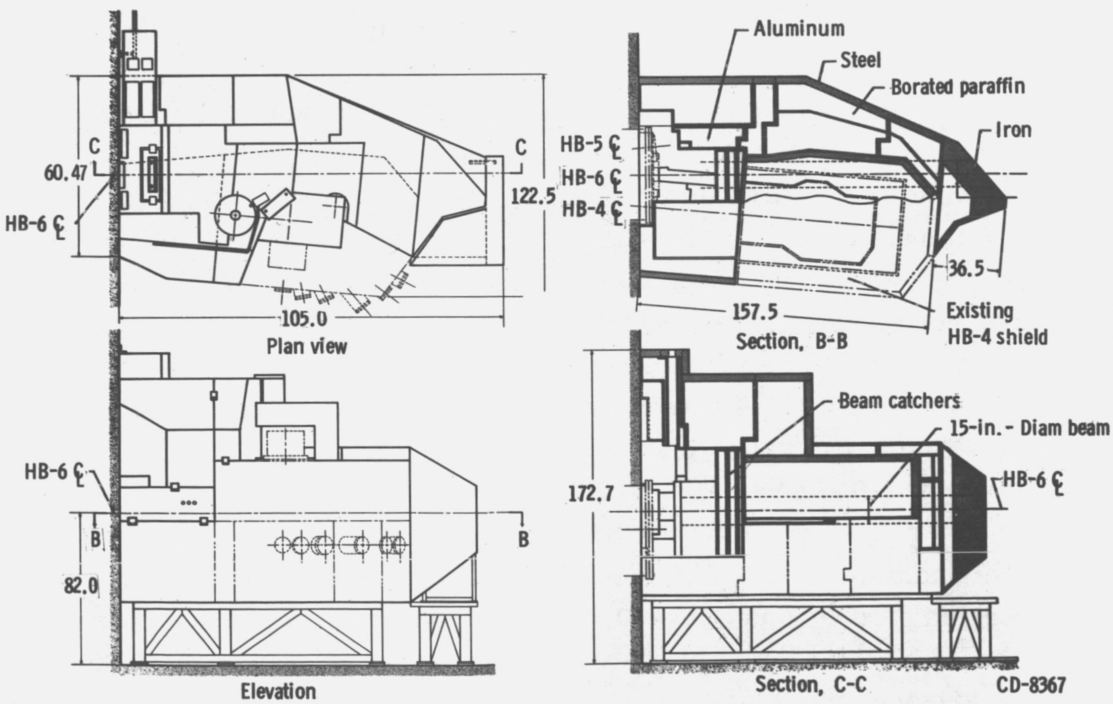
For direct radiations, the minimum shield thicknesses provided were 9.6 feet (2.9 m) of borated paraffin and 2 feet (0.61 m) of iron, including the thickness of the pyramidal-shaped block at the rear of the shielding array. Since no offsets exist on the outside shield surface, this block served to prevent radiation streaming due to possible misalinement between the two shielding assemblies. Additional shielding, in the form of an extension on the top shield surface along the HB-4 centerline, was required to prevent



(a) View showing HB-6 shield assembly.



(b) View showing modified HB-4 shield assembly.



(c) Plan and elevation views of shield surface and cross section views along vertical and horizontal centerlines. (All dimensions are in inches.)

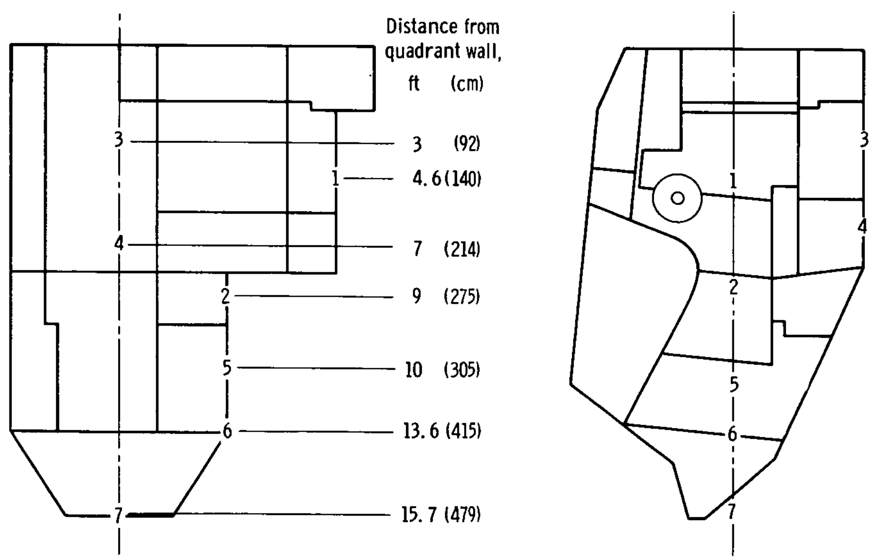
Figure 7. - HB-6 beamhole shield assembly.

radiation streaming from a rotating turret mechanism associated with the HB-4 beam-hole experiment.

OPERATIONAL SHIELD TEST

An operational shield test was conducted to evaluate the biological effectiveness of the shield. Dose points were selected on the top, side, and rear surfaces of the shield along the projections of the HB-6 duct centerline. Gamma dose rates were measured with a Geiger-Muller tube calibrated with a radium 226 source, and fast-neutron dose rates were measured with a proton recoil counter. In general, the measured neutron and gamma levels were within a factor of 2 of the dose rates predicted by QAD and G-33 computer code analyses.

A comparison of measured and calculated scatter dose rates is shown in figures 8 and 9. Figure 8 is a tabulation of neutron and gamma dose rates at various points on



Point	Location	Gamma dose rate, m rem/hr		Neutron dose rate, m rem/hr	
		Measured	Calculated	Measured	Calculated
1	Top	0.4	<1	<1	0.3
2	Top	1.2	[a]4.5 to 26.5		1.0
3	Side	2.0	1.0		.3
4	Side	1.5	1.0		.3
5	Top	3.9	[a]1.1 to 5.3		<.1
6	Top	.9	<.1		<.1
7	Rear	.1	<.1		.3

[a]Varies with test-package thickness.

Figure 8. - Comparison of measured and calculated neutron and gamma dose rates on shield surface.

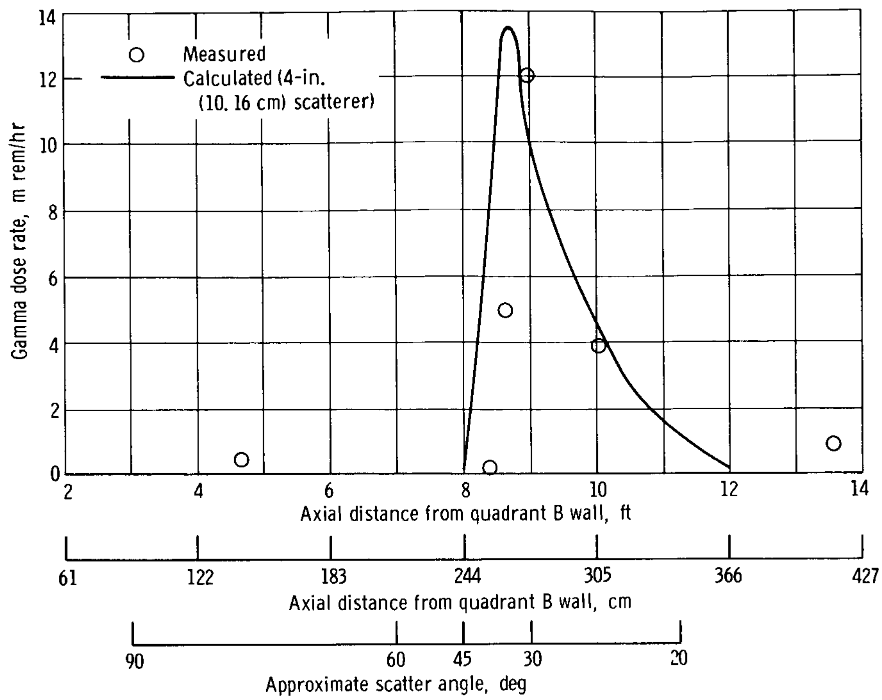


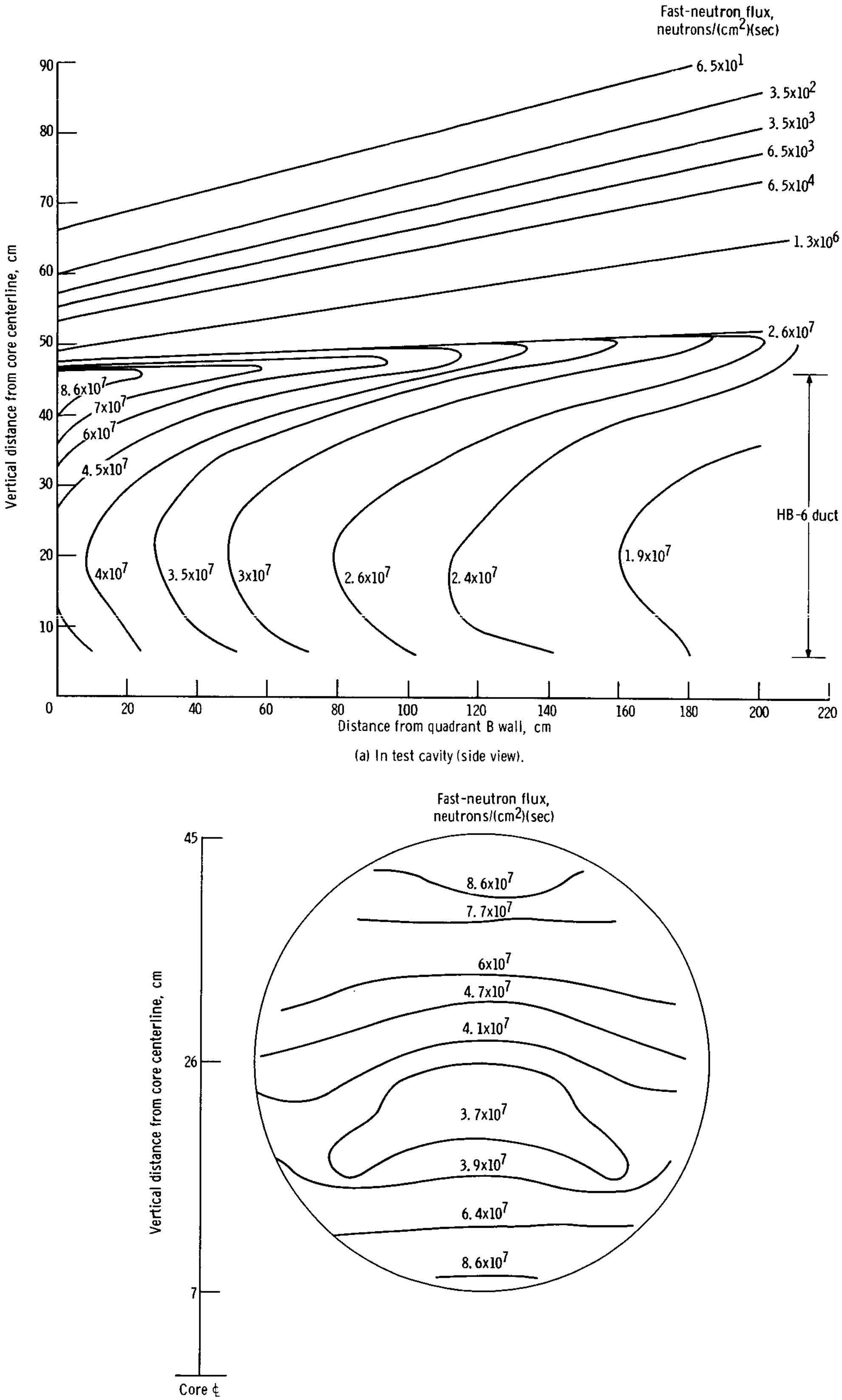
Figure 9. - Comparison of measured and calculated gamma dose rates along top of shield as function of scatter angle and axial distance from quadrant B wall.

the shield surface, while figure 9 is a comparison of scattered gamma dose rates along a projection of the HB-6 centerline on the top of the shield. No appreciable neutron dose rates were detected at any point on the shield surface. Also, no radiation streaming was observed, indicating the effectiveness of offsets in the shield design.

ADDITIONAL CALCULATIONS

Fast-Neutron Flux Map

The QAD digital computer code was used to calculate a fast-neutron flux map at the test-chamber location. This map provided an estimate of the spatial variation of the fast flux. A grid network composed of 143 detector points provided adequate coverage of the test-cavity area. Figure 10(a) is a side view of the fast-neutron flux distribution into the test cavity along the duct centerline, and figure 10(b) is an end view taken through a vertical section at the quadrant wall. Both figures present data for a voided HT-1 duct. A maximum fast flux of 8.6×10^{7} neutrons per square centimeter per second was calculated at the top and bottom of the HB-6 duct, and 3.7×10^{7} neutrons per square centimeter per second was the minimum flux calculated slightly below the duct centerline.



(a) In test cavity (side view).

(b) At quadrant B wall (end view).

Figure 10. - Fast-neutron flux map. HT-1 voided, HB-6 voided; shim rods at 27.8 inches.

Effect of Flooding HT-1 Duct

The overall effect of flooding the HT-1 duct was to lower neutron fluxes and gamma dose rates in the test cavity. Calculations performed with the QAD code show the decrease in neutron flux to vary from a factor of 1.3 at the bottom of the duct to a factor of 2.3 at the top. This effect is shown for two locations in the test cavity (fig. 11). The maximum fast flux on the HB-6 vertical duct centerline was calculated to be 3.2×10^{7} neutrons per square centimeter per second at the quadrant wall and 2.4×10^{7} neutrons per square centimeter per second 2 feet from the wall. Similar calculations for the gamma dose rate are plotted in figure 12, which shows the decrease in gamma dose rate to vary from a factor of 1.0 at the bottom of the duct to a factor of 1.2 at the top.

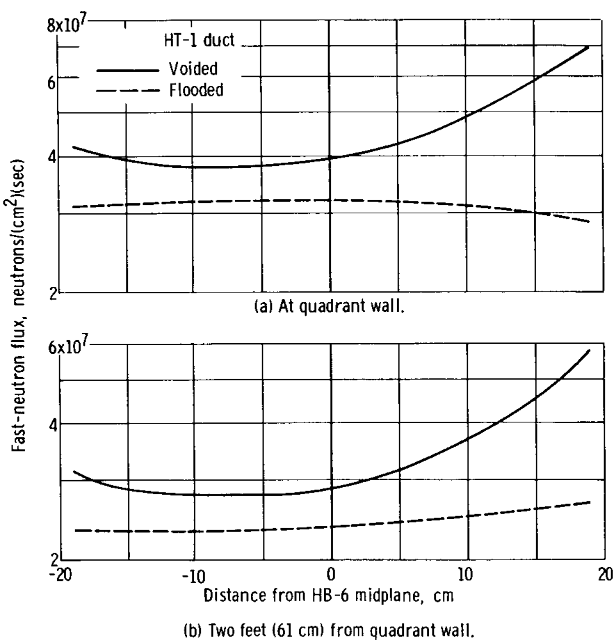


Figure 11. - Effect of flooded HT-1 duct on fast-neutron flux in quadrant B test cavity. Shim rods at 27.8 inches.

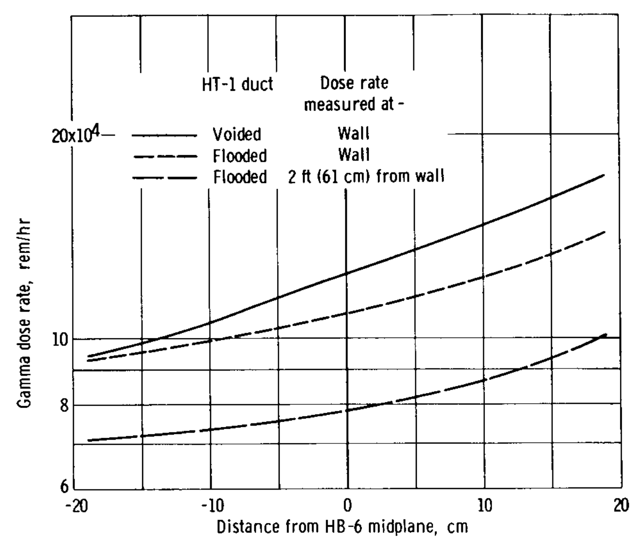


Figure 12. - Effect of flooded HT-1 duct on gamma dose rate in quadrant B test cavity. Shim rods at 27.8 inches.

Effect of Selectively Flooding HB-6 Beamhole

The effect of selectively water flooding the compartmentalized tank in the HB-6 beamhole was calculated with the QAD code. Water thicknesses were determined by the dimensions of the compartments. Any combination of the compartment dimensions, 6 feet, 12 inches, 6 inches, 3 inches, and 1.5 inches (183, 30.5, 15.2, 7.6, and 3.8 cm) can be flooded. The primary purpose of these compartments is to vary the fast-neutron flux reaching the test cavity. A secondary function is to provide emergency neutron and gamma shielding. The effect of flooding the compartments on the fast-neutron flux at

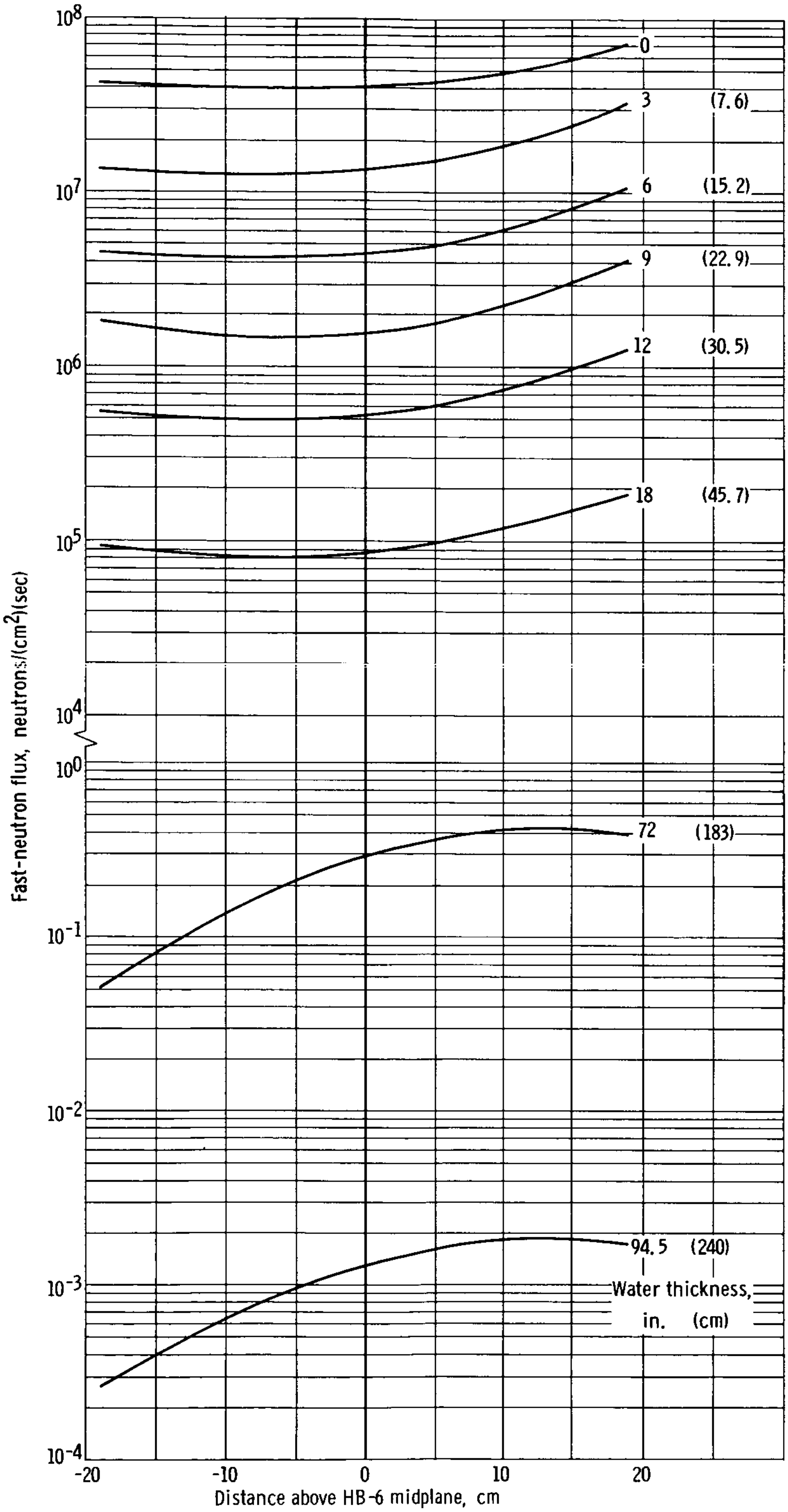


Figure 13. - Effect of filling HB-6 water compartments on fast-neutron flux at quadrant B wall. HT-1 voided; shim rods at 27.8 inches.

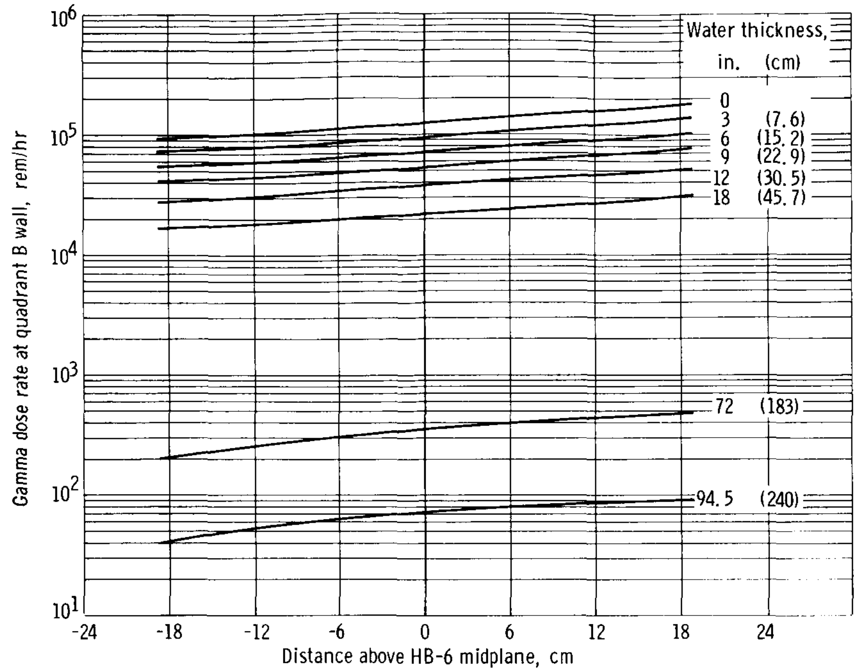


Figure 14. - Gamma dose as function of flooding HB-6 water compartments to various thicknesses. HT-1 voided; shim rods at 27.8 inches.

the quadrant wall is shown in figure 13. The fast flux decreases by about a factor of 3 for every 3 inches (7.6 cm) of water up to a total water thickness of 18 inches (46 cm) A total attenuation factor of about 2×10^{10} was obtained when all compartments were flooded.

A similar effect for gamma rays is shown in figure 14, which shows a decrease of a factor of about 1.4 in gamma dose rate for every 3 inches (7.6 cm) of water up to a total thickness of 18 inches (46 cm). A total attenuation factor of about 2×10^3 was obtained when all compartments were flooded.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 9, 1967,
120-27-06-07-22.

APPENDIX - GENERAL DESCRIPTION OF DIGITAL COMPUTER SHIELD PROGRAMS

QAD

QAD is a digital computer program originally written at Los Alamos Scientific Laboratory and designed to calculate the effect of neutron and gamma radiation from a volume-distributed source in a source-shield geometry generally describable by quadratic surfaces. Neutron and gamma dose rates, gamma heating rates, and other derived quantities may be estimated subject to the limitations of the line-of-sight method, neutron-removal theory, the use of a single gamma-buildup factor, and the extent to which the actual geometry can be represented by quadratic equations describing surfaces.

The QAD version presently used at the Lewis Research Center has been modified to include an additional feature which enables the representation of source-shield and reactor geometries not possible with the Los Alamos version. Specifically, reactor (source) geometry has been generalized to include spherical, rectangular, and skew surfaces.

The calculational procedure for gamma radiation is as follows: (1) The source region is divided into a number of point isotropic sources. (2) The distance, with associated energy-dependent exponential attenuation and buildup, is computed through all regions intercepted by the line-of-sight from the source point to the desired dose or receiver point. After determination of the distances through all zones, the sum of the products of the distances and attenuation coefficients for all materials are made. From this sum and the total source-receiver separation distance, the material and geometric attenuation and the buildup factor are computed for each energy group. This process is then continued until the contribution from all source points has been determined. After the application of suitable energy-dependent conversion factors, the results (gamma heating or dose rate) for each energy group and the total response, both with and without buildup, are recorded for output. The next receiver point is then treated in the same manner until all receivers have been computed.

Neutron dose rates are calculated similarly except that attenuation is treated with removal cross sections for nonhydrogenous materials combined with an empirically derived method (Albert-Welton point kernel) for hydrogenous materials.

G-33

G-33 is a digital computer program, obtained from the Los Alamos Scientific Laboratory, to calculate the effect of single-scattered gamma radiation from a scattering volume in a source-shield geometry generally describable by quadratic surfaces. Direct and scattered gamma dose rates and scattered gamma energy spectra may be estimated subject to the limitations of a point source, a single buildup factor, and the extent to which the actual geometry can be represented by quadratic equations describing surfaces.

The method of calculation involves dividing the scatter volume into a number of smaller orthogonal scattering volumes, and computing the distance, with associated exponential attenuation, from the source point to the scatter volume of interest. The uncollided energy flux incident upon each scatter volume from the point source is then computed. Based on the coordinates of a particular scatter volume and detector point, the cosine of the scattering angle, the scattered energy, and the Klein-Nishina differential scattering cross section are calculated. Dose rates are then computed for each of the scattered energies and the response, both with and without buildup, is the scattered dose rate recorded for output.

NAAC

NAAC is a digital computer program to calculate the neutron-induced gamma radioactivity in any thickness of composite material. This program is an adaption of the Westinghouse codes ACT I and ACT II (ref. 4). Program control was altered to produce a more efficient use of machine-core storage and running time. The program calculates the energy-dependent gamma source strength and adjusts cross sections for resonance self-shielding, for materials exposed to a four-group neutron flux, as a function of exposure and decay times. Neutron activition may occur by (n, γ), (n, p), (n, α), $(n, 2n)$, or (n, n') interactions in a material composed of as many as 20 elements. NAAC calculates this activity for up to 50 different time increments during and after irradiation.

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